NRC Staff Technical Position for North Anna Hot Leg to Steam Generator Nozzle Flaws

Executive Summary

NRC/Region II requested assistance from NRC/NRR and NRC/RES staff in resolving safety issues for flaws found in a North Anna (NA) hot leg to steam generator nozzle during an early-2012 refueling outage. Region II posed three questions to NRR and RES involving flaw detectability, non-conforming condition, and flaw propagation due to pre-overlay machining. These questions and NRR and RES response are summarized as follows. Although multiple flaws were detected in the early-2012 outage, the following summary refers only to a single limiting case of the deepest flaw.

Question 1: What is the likelihood that a detectable flaw was present in the spring 2009 refueling outage and grew to the size observed in the early 2012 outage?

> **Consensus NRR and RES Response: The staff has concluded that it is highly likely that a detectable flaw was present in the 2009 outage and grew to the size observed in 2012. A conservative idealized flaw growth analysis based on ASME Code Section XI flaw evaluation procedures gives a 48% upper bound probability that a flaw was detectable in 2009 and grew to the size observed in 2012. A more accurate deterministic natural flaw growth analysis indicates with greater likelihood that a flaw was present and detectable in 2009 and grew to the size observed in 2012.**

Question 2: What is the likelihood that a flaw was unacceptable between 2009 and 2012, placing the plant in a non-conforming condition?

> **Consensus NRR and RES Response: Given that the flaw was observed by the licensee following pre-weld overlay machining to be approximately 80% through-wall, and the ASME Code upper bound acceptability limit is 75% through-wall, the staff believes that the plant was operated in a non-conforming condition. The conservative idealized flaw growth analysis determined the flaw to be greater than 75% through-wall for 3.2 +/- 1.2 months. Based on the more accurate natural flaw growth analysis, the flaw was greater than 75% through-wall for approximately 4 months.**

Question 3: What is the likelihood that the flaws could have grown during the pre-weld overlay machining process?

> **Consensus NRR and RES Response: The applied stress intensity factor for both the idealized flaw growth and natural flaw growth models varies between 30 and 100 MPa√m as the flaw grows through-wall. The fracture toughness of Alloy 82/182 at room temperature is approximately 290 - 374 MPa√m. Therefore, the staff believes that it is highly unlikely that stress redistribution during the machining process would have independently lead to flaw growth. Lower fracture toughness values for Alloy 82/182 (approximately 50 MPa√m) have been measured, however these values correspond to water environments that have significantly higher hydrogen concentrations than is typical for operating PWRs.**

1. Introduction

NRC/Region II requested assistance from NRC/NRR and NRC/RES staff in resolving safety issues for flaws found in a North Anna (NA) hot leg to steam generator nozzle during an early-2012 refueling outage. Region II posed the following three questions to NRR and RES involving flaw detectability, non-conforming condition, and flaw propagation due to pre-overlay machining:

- What is the likelihood that a flaw was undetectable in the spring 2009 refueling outage and grew to the size observed in the early 2012 outage?
- What is the likelihood that a flaw was unacceptable between 2009 and 2012, placing the plant in a non-conforming condition?
- What is the likelihood that the flaws could have grown during the pre-weld overlay machining process?

Although multiple flaws were detected in the early-2012 outage, the following summary refers only to a single limiting case of the deepest flaw.

NRC staff and its contractor have analyzed the NA weld to answer the three questions listed above. This document summarizes the analyses performed, and provides the staff's consensus technical position in response to each question. The following sections describe the weld residual stress analysis, idealized flaw growth analysis, natural flaw growth analysis, and a review of the licensee's flaw evaluation.

2. Weld Residual Stress

The NRC staff and its contractor, Engineering Mechanics Corporation of Columbus (Emc2), completed a detailed weld residual stress analysis using typical computational weld modeling processes that have been validated by mock-up testing in the nuclear industry. The NA hot leg to steam generator nozzle weld is a double-vee groove weld with two repairs (large inner diameter repair and small outer diameter repair)in the region where through-wall flaws were observed following pre-overlay machining. The weld material is Alloy 82 for the butter and Alloy 182 for the main weld and repair welds. The nozzle and safe end materials are assumed to be A508 and 316 stainless steel.

The axi-symmetric finite element model for the nozzle is shown in Figure 1. The weld procedure simulated consisted of application of the Alloy 82 butter layer, post weld heat treat, machining of the butter, application of the Alloy 182 weld (blue outline in Figure 1), machining of the repair grooves followed by application of the repair welds (red outline in Figure 1), and then finally application of the closure stainless steel weld. Note that the ID repair weld is quite large and slightly offset axially from the original weld.

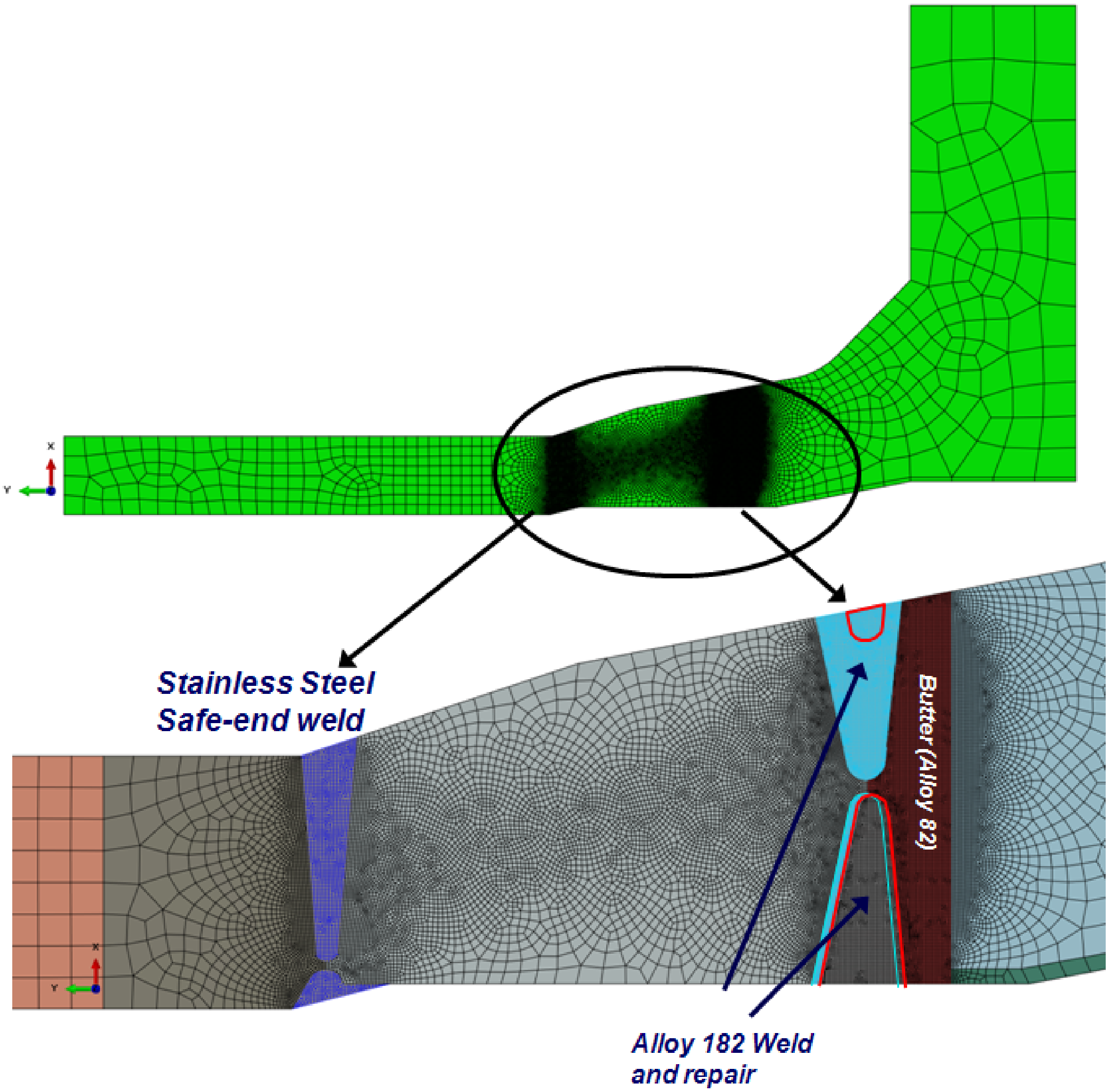

Figure 1 Overall finite element model for North Anna SG nozzle

WRS validation studies have shown that the assumed strain hardening law will have a significant impact on calculated results. For this study, analyses were performed using isotropic, non-linear kinematic, and mixed strain hardening.

The flaws observed at NA are axially oriented. Axial flaws are driven by hoop weld stresses, hence the WRS results are presented for this stress component.

Figure 2 shows the hoop stresses through the centerline of the dissimilar metal weld, for the three strain hardening laws. Figure 3 shows a contour plot of the nozzle hoop stress distribution.

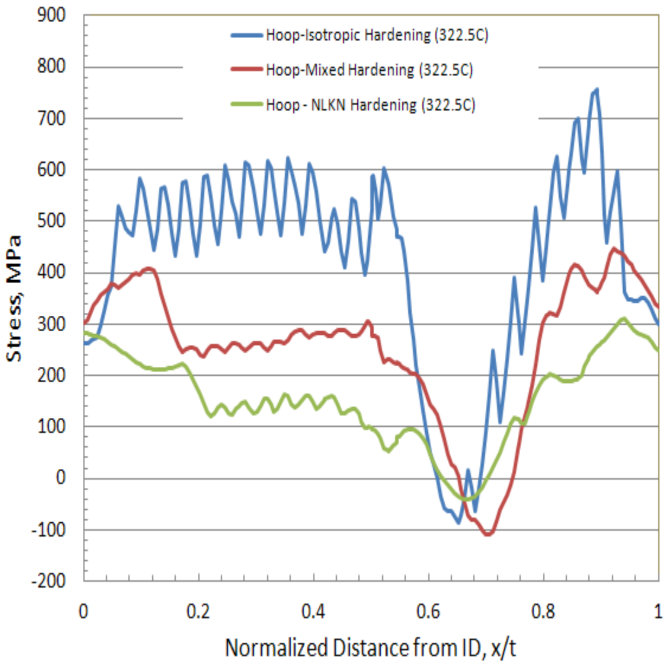

Figure 2 Line plots of hoop stress in the centerline of DM weld

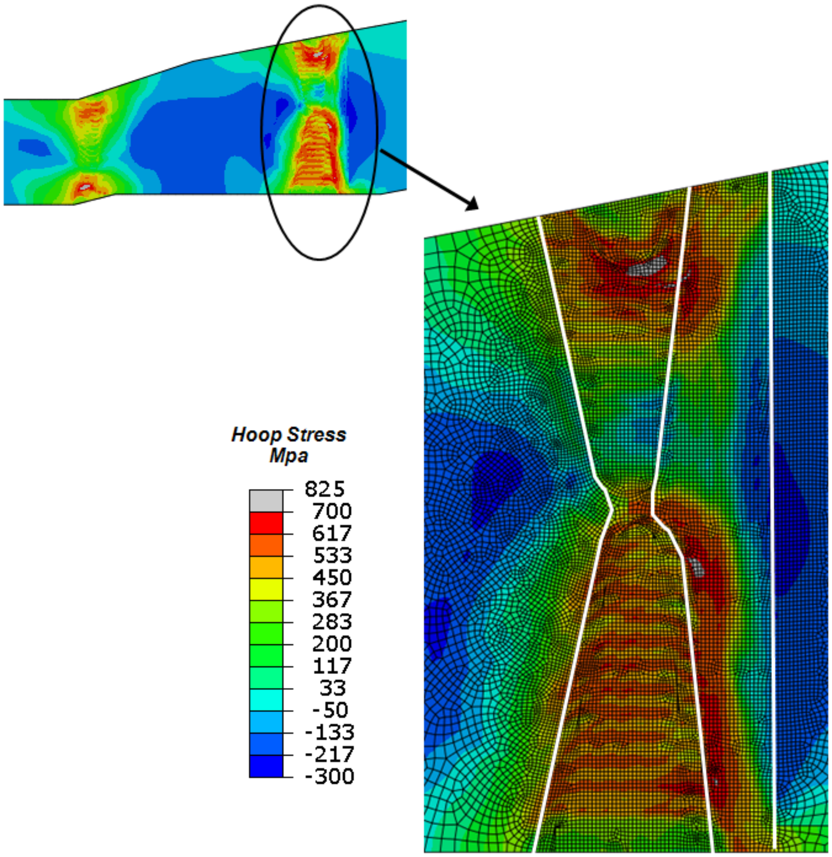

Figure 3 Contour plots of hoop stress in the DM weld

3. Idealized Flaw Growth Analysis

The flaws found in the steam generator dissimilar metal weld were all axially orientated and varying depths. Since these are axially orientated flaws, the loads that will affect the PWSCC growth will be the weld residual stress (WRS) and hoop stress due to pressure. The weld residual stress used in the idealized flaw analyses are given in Figure 4. In this case a series of weld residual stress were assumed in order to account for uncertainty in the analyses. Finite element weld residual stress results with and without repairs are shown in Figure 4. For the idealized analyses, a polynomial representation of the WRS is needed, and those results are also shown in the figure. For the case with repair, two curve fits were made. The first, labeled fit #1, is the best fit to the data. The second, labeled fit #2, is fit with a bias toward the compressive stresses in order to capture the behavior more accurately. In addition, WRS equal to the as-welded yield strength and 50% of the as-welded yield strength were also considered.

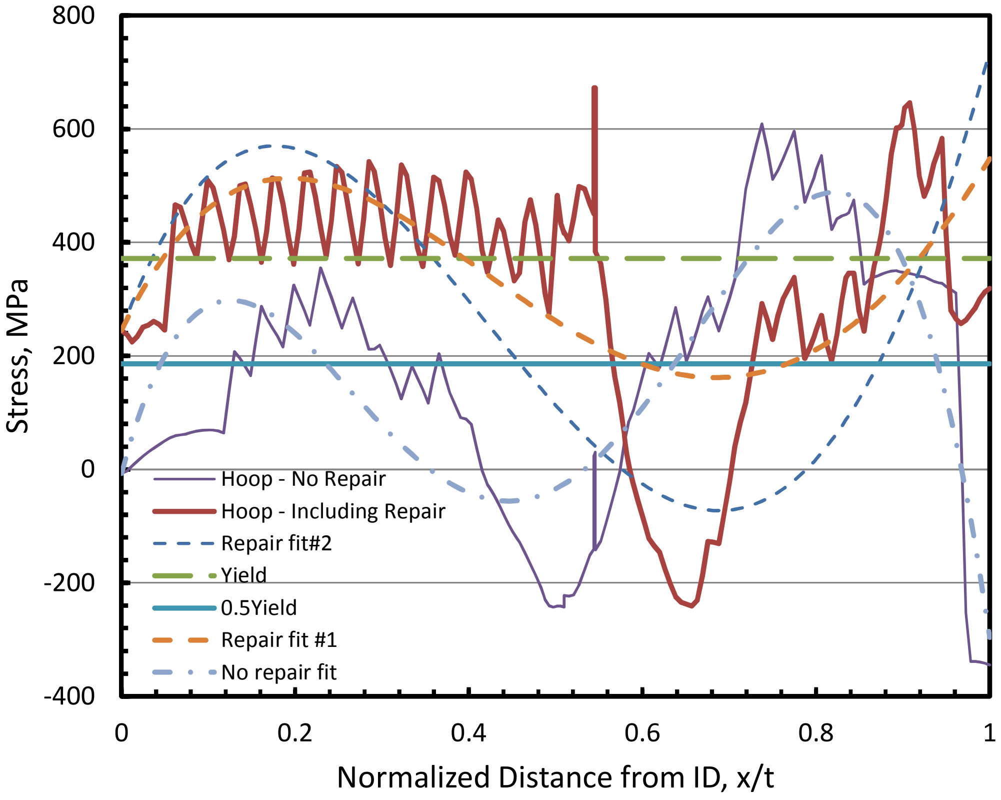

Figure 4 Weld residual stress used in analyses

For axial SCC growth within a dissimilar metal weld, the length of the flaw is limited to the width of the susceptible material. To account for variability in crack growth rates, the distribution of values reported in EPRI MRP-115, “Materials Reliability Program Crack Growth Rates for Evaluating Primary Water Stress Corrosion Cracking (PWSCC) of Alloy 82, 182, and 132 Welds” was used. Figure 6 shows the results of the idealized flaw growth analyses. If the probability values are extracted from this figure at a/t=0.1

(NDE detection limit), an estimate of the likelihood a flaw was present in 2009, missed by an inspection and reached 80% deep in 33 months can be made.

Based on the WRS with repair, there is a 52% chance (or 52% of the flaw growth rates measured would cause) a 10% flaw present in 2009 would have grown greater than 80% through wall in 33 months or less, i.e. there is a 48% chance a flaw was present and beyond the NDE detection limit in 2009 and grew to 80% through wall in 33 months.

Based on the WRS without repair, there is about a 1% chance (or 1% of the flaw growth rates measured would cause) a 10% flaw present in 2009 would have grown greater than 80% through wall in 33 months or less, i.e. there is a 99% chance a flaw was present and beyond the NDE detection limit in 2009 and grew to 80% in 33 months.

Therefore, the lower the residual stress, the more likely a flaw larger than the detection limit was present in 2009 and grew to 80% deep in 33 months.

The idealized flaw growth analysis also demonstrates that the flaw had exceeded the ASME Code acceptability limit of 75% through-wall for 3.2 +/- 1.2 months.

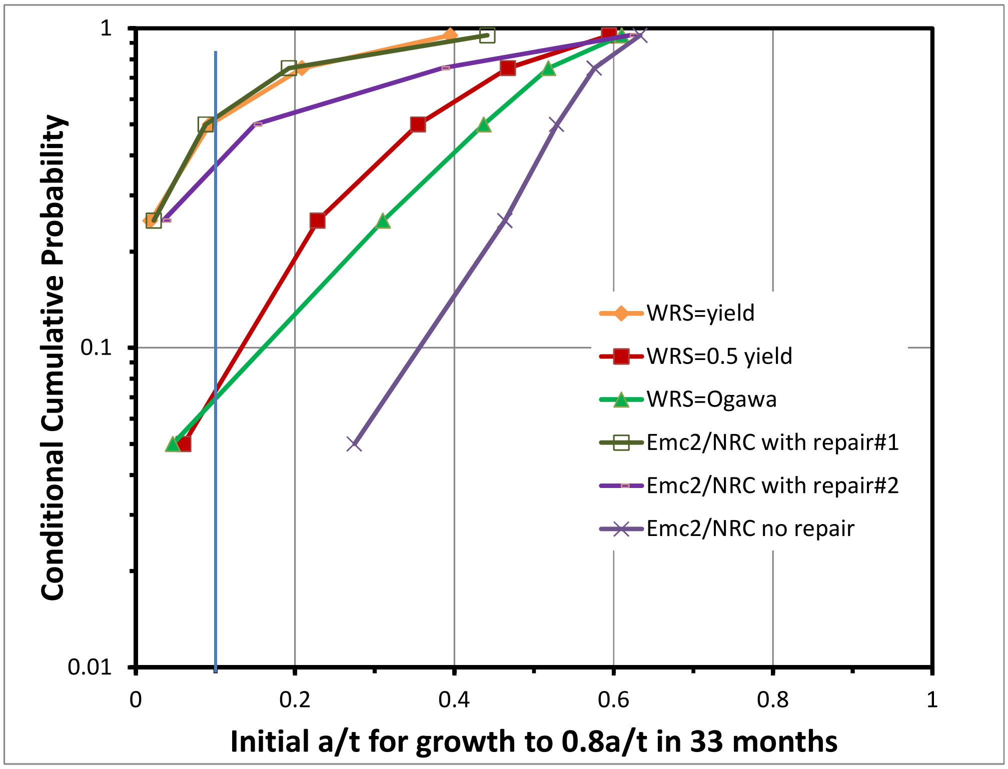

Figure 6 Conditional probability that a flaw would grow to 80% through-wall in 33 months

4. Natural Flaw Growth Analysis

Natural flaw growth analyses were performed on the North Anna steam generator dissimilar metal weld. These flaws are driven by primary water stress corrosion cracking (PWSCC) and tensile stresses caused by the WRS and the service loading. For axial flaw growth in the DM weld, the loading consists of internal nozzle pressure and flaw face pressure (15.5 Mpa) combined with the WRS from Figure 4. In the natural flaw growth analysis method, a finite element analysis is performed at each increment of flaw growth to calculate stress intensity factors along the crack front. Using the stress intensity factor results and the assumed flaw growth law and 75% flaw growth rate from EPRI MRP-115, an increment of crack advance is calculated and the procedure is repeated. For this study, primary water stress corrosion cracking (PWSCC) of dissimilar metal (DM) welds is the only subcritical cracking mechanism that was considered.

Typically, the flaw growth increments were kept to under 10 mm, with smaller increments as the crack depth approached mid thickness. For every crack growth step, the WRS were mapped to the flaw mesh and the WRS were compared to ensure accuracy and as a check of the proper boundary conditions and surface loading.

The evolution of the flaw and the corresponding complex flaw shapes can be seen in Figure 7. The initial flaw shape (at time = 0 years) was assumed to be 6 mm deep and a total of 12 mm in width as seen with the ‘blue’ shape in Figure 9. As seen, the flaw reaches the right side weld butter line at about 0.46 years and then begins to grow slower in the butter. The flaw begins to touch the safe end at about 0.64 years and then the flaw follows the fusion boundary between the weld and safe-end as it grows deeper. At 1.17 years the flaw nearly reaches the butter – nozzle line and then can only grow vertically from that point on. At this time the depth is about 54 mm. The flaw depth growth slows down just past the neck area after about 1.76 years to 4 years. This is the region of the weld shape neck down where most of the material is represented by Alloy 82 butter. In addition, this is the region where the weld residual stresses become slightly negative also contributing to a slower growth rate.

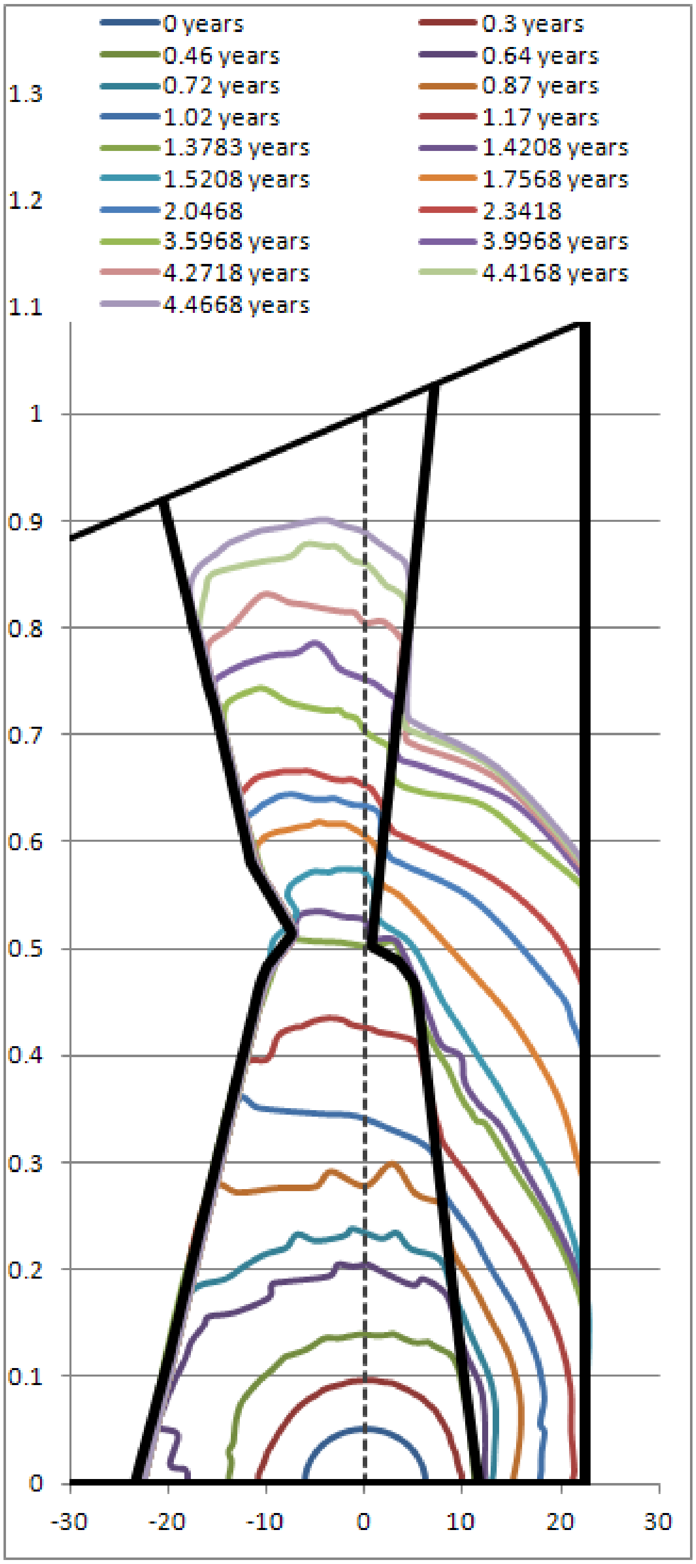

Figure 7 Flaw growth evolution in the North Anna SG nozzle

Figure 8 shows the flaw depth at the deepest point versus time. The flaw growth rate falls near the narrow region between the double-vees where the weld residual stress is lower, and a larger portion of the flaw is in the weld butter (with corresponding lower flaw growth). Later, the flaw growth rate increases as the deepest point (in the main DM weld with higher flaw growth rate) experiences higher weld residual stress.

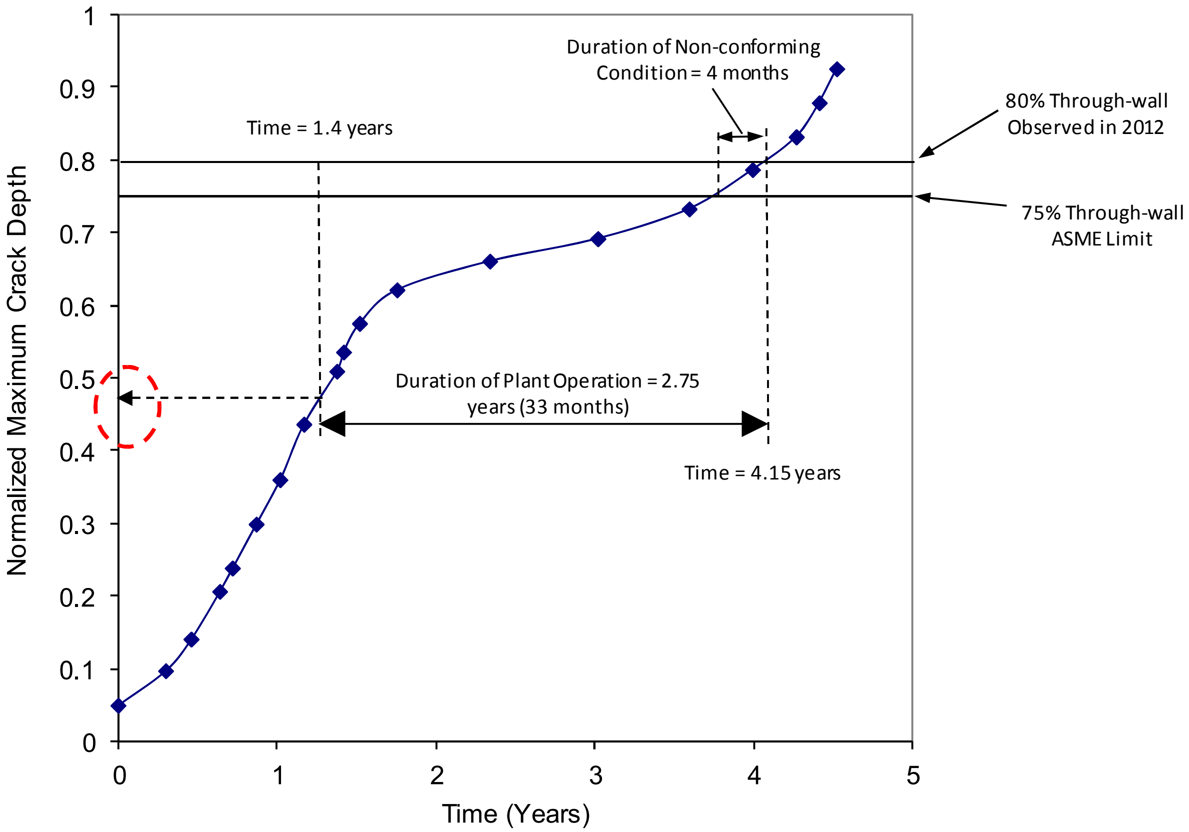

Figure 8 Flaw growth estimate from 2009 outage to 2012

Figure 8 allows an estimate of the time that the flaw grew during the 2.75 years from the 2009 inspection to 80% this spring. Starting with the observed 80% through-wall flaw in 2012, and moving back in time 33 months (corresponding to the preceding operating cycle), Figure 8 shows that the estimated flaw depth was 47% in the 2009 outage. Similarly, starting with the 80% flaw in 2012, it is seen that the 75% ASME Code acceptability limit would have been reached about 4 months prior.

5. Licensee's Flaw Evaluation

NRC/RES staff members were allowed to view the licensee's proprietary flaw evaluation document at the Westinghouse office in Rockville, MD. The document was prepared in 2008 by Westinghouse in a handbook format, and provides a "generic" flaw evaluation typically done prior to refueling outages. NRC staff identified the following concerns:

- WRS assumed: combination of MRP-113 (RPV nozzle - 1=2.3", Di/t=13) and ASME (assuming 30ksi yeild strength). The licensee did not perform a geometry-specific WRS analysis.
- Constant aspect ratio flaw growth predictions. 2c/a range from 2 to 10 (not realistic)
- Used a 3rd order curve fit to the WRS from MRP-113 (but never show the fit)
- Used Newman-Raju stress intensity solutions (newer and more accurate solutions are available)

The results show that for the inlet analyses with axial flaws, about 75% of their runs showed the flaw was less than 10% in 2009 if it was 75% in 2012.